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# Determination of the optimum binder content of warm mix asphalt incorporating Rediset using response surface method

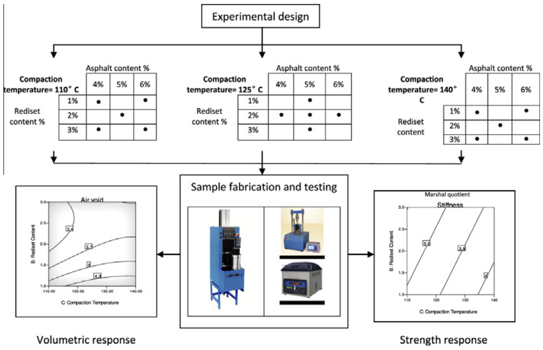
Meor Othman Hamzah [a],*, Babak Golchin [a], Ching Thian Tye [b]

[a] School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia,14300 Nibong Tebal, Seberang Perai Selatan, Penang, Malaysia
[b] School of Chemical Engineering, Engineering Campus, Universiti Sains Malaysia,14300 Nibong Tebal, Seberang Perai Selatan, Penang, Malaysia

## HIGHLIGHTS

- RSM can be used to determine the optimum binder content of WMA.
- The OBC of warm mix asphalt containing Rediset is not significantly different from the OBC of hot mix asphalt.
- Higher Rediset content decreases the Marshall quotient of warm mix asphalt.

## GRAPHICAL ABSTRACT



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## ABSTRACT

This paper presents the effects of compaction temperatures (110–140 °C), Rediset contents (1–3%) and asphalt binder contents (4–6%) on the volumetric and strength properties of warm mix asphalt to optimize the binder content (OBC). For this purpose, an experimental matrix was planned based on the central composite design for three factors: Rediset content, compaction temperature and asphalt binder content. In addition, the volumetric and strength behavior of the samples were analyzed using response surface method, while the OBC was obtained from the results. The results showed that the maximum variation of the OBC for all cases is 0.25% and the OBC of warm mix asphalt compacted at high temperature is slightly higher than the OBC of warm mix asphalt compacted at lower temperature. It was also found that the OBC can be easily determined for a defined condition by using several factors simultaneously (for example binder content incorporating compaction temperature and additive content) and their relationships with strength and volumetric responses by using response surface method.

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## 1. Introduction

The optimum binder content (OBC) refers to the amount of asphalt binder that balances different desirable mixture properties for each combination of aggregate type, aggregate gradation, additive type, additive dosage and binder type. In warm mix asphalt (WMA) studies, the optimum binder content of hot mix asphalts (HMA) are usually used for fabrication of warm mix asphalt [1–5]. The use of the same binder content is based on the assumption that the difference between the optimum binder content of WMA and HMA is very small. Another reason is that some researchers usually tend to compare HMA and WMA behavior without taking into account variation in binder content. Nevertheless, some other researchers determined the optimum binder content of WMA using a particular mix design method, and this binder content was used to evaluate mix properties [6–8]. Some literatures recommended [9,10] and discussed [11,12] the binder content without carrying out any optimization process. The main objective of this research is to propose a new approach for

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* Corresponding author. Tel.: +60 45996210; fax: +60 45941009.
*E-mail address:* cemeor@yahoo.com (M.O. Hamzah).

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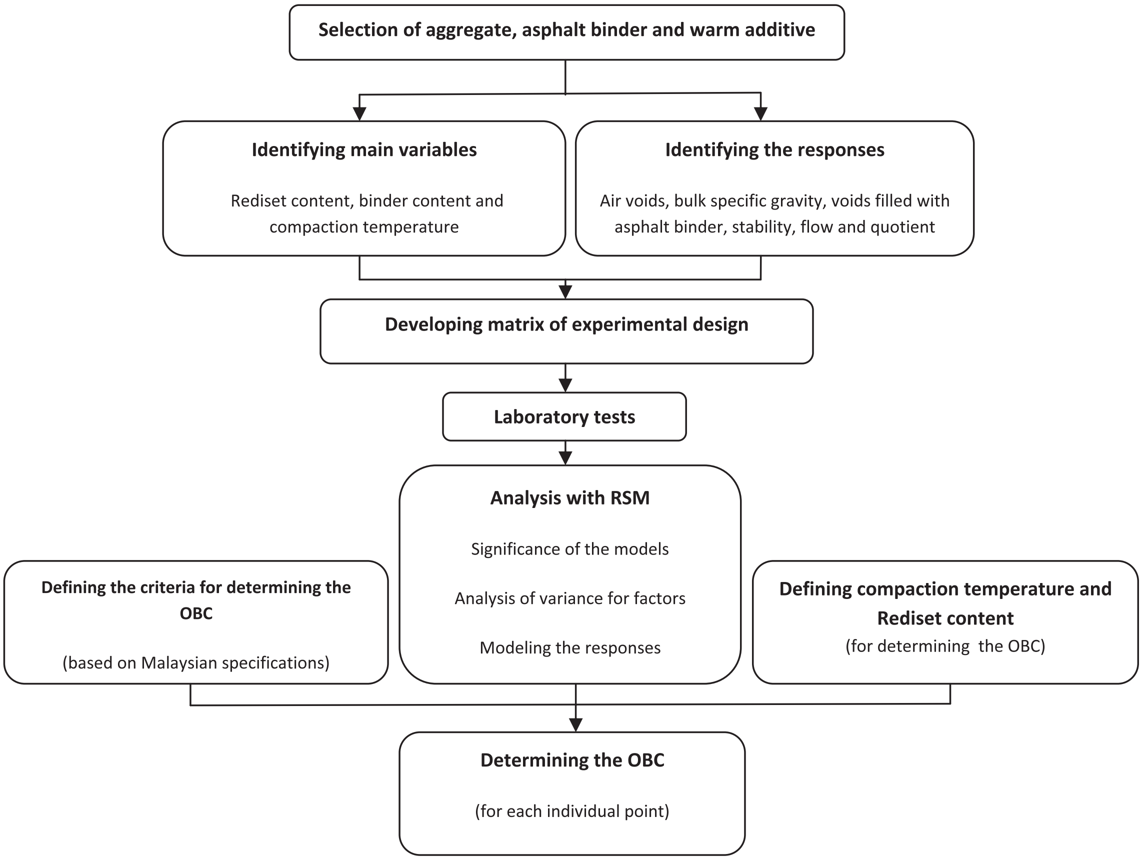

Selection of aggregate, asphalt binder and warm additive
Identifying main variables
Rediset content, binder content and compaction temperature
Identifying the responses
Air voids, bulk specific gravity, voids filled with asphalt binder, stability, flow and quotient
Developing matrix of experimental design
Laboratory tests
Analysis with RSM
Significance of the models
Analysis of variance for factors
Modeling the responses
Defining the criteria for determining the OBC
(based on Malaysian specifications)
Defining compaction temperature and Rediset content
(for determining the OBC)
Determining the OBC
(for each individual point)

**Fig. 1.** Research process.

determining the OBC of warm mix asphalt incorporating various Rediset content at different compaction temperatures based on response surface method (RSM). The paper also investigates the interaction effect of experimental factors (Rediset content, binder content, and compaction temperature) on the strength and volumetric properties of warm mix asphalt.

RSM is a collection of statistical methods for designing experiments, developing models and assessing the effects of the experimental factors and optimizing the process [13,14]. This method has been effectively used in various disciplines such as

**Table 1**
Matrix of experimental design.

| No. | A<br>Binder content (%) | B<br>Resident content (%) | C<br>Compaction temperature (°C) |
|---|---|---|---|
| 1 | 6 | 1 | 110 |
| 2 | 6 | 3 | 110 |
| 3 | 4 | 3 | 110 |
| 4 | 5 | 2 | 110 |
| 5 | 4 | 1 | 110 |
| 6 | 5 | 2 | 125 |
| 7 | 5 | 2 | 125 |
| 8 | 5 | 2 | 125 |
| 9 | 5 | 3 | 125 |
| 10 | 5 | 2 | 125 |
| 11 | 5 | 1 | 125 |
| 12 | 4 | 2 | 125 |
| 13 | 5 | 2 | 125 |
| 14 | 6 | 2 | 125 |
| 15 | 5 | 2 | 125 |
| 16 | 6 | 3 | 140 |
| 17 | 4 | 3 | 140 |
| 18 | 5 | 2 | 140 |
| 19 | 4 | 1 | 140 |
| 20 | 6 | 1 | 140 |

**Table 2**
Responses and their acceptable range based on the Malaysian specifications [23].

| Responses | Acceptable range | Parameters for determining the OBC* |
|---|---|---|
| *Strength response* | | |
| Stability | >8000 N | Peak point |
| Flow | 2.0–4.0 mm | Flow = 3 mm |
| Marshall quotient | >2000 N/mm | - |
| *Volumetric response* | | |
| Air voids in mix | 3.0–5.0% | Air voids = 4% |
| $G_{mb}$** | – | Peak point |
| VFA*** | 70–80% | VFA = 75% |

*The average value of this column is used for determining the OBC.

**Bulk specific gravity.

***Voids in aggregate filled with asphalt binder.

**Table 3**
Aggregate gradation for AC 14 wearing course according to the Malaysian specifications [23].

| Sieve size (mm) | Percentage passing (Malaysian specification) | Percentage passing (for this study) |
|---|---|---|
| 20 | 100 | 100 |
| 14 | 90–100 | 95 |
| 10 | 76–86 | 81 |
| 5 | 50–62 | 56 |
| 3.35 | 40–54 | 47 |
| 1.18 | 18–34 | 26 |
| 0.425 | 12–24 | 18 |
| 0.150 | 6–14 | 10 |
| 0.075 | 4–8 | 6 |

**Table 4**
Properties of granite aggregates used.

| Property | Test result | Test method |
|---|---|---|
| Coarse aggregates bulk specific gravity | 2.62 | AASHTO T85 |
| Absorption (%) | 0.40 | AASHTO T85 |
| Fine aggregates bulk specific gravity | 2.57 | AASHTO T84 |
| Absorption (%) | 0.54 | AASHTO T84 |
| Fine aggregate angularity (%) | 47.3 | AASHTO T33 (Method A) |
| Course aggregate angularity (%) | 49.5 | AASHTO TP56 (Method A) |
| Flat and elongated (%) | 23.3 | BS 812-105 |
| Los Angeles abrasion (%) | 23.86 | AASHTO T96 |
| Aggregate crushing value (%) | 19.25 | BS 812-110 |

**Table 5**
Properties of asphalt binder used.

| Aging condition | Technical properties | Value |
|---|---|---|
| Original binder | Viscosity at 135 °C (Pa s) | 0.38 |
| | $G^*/\sin\delta$ at 64 °C (Pa) | 1653 |
| | Failure temperature (°C) | 68 |
| | Softening point (°C) | 45 |
| | Penetration (0.1 mm) | 80 |
| | Ductility (cm) | >100 |
| | Flash point (°C) | 331 |
| Short-term aged binder (RTFO) | $G^*/\sin\delta$ at 64 °C (Pa) | 2442 |
| | Failure temperature | 65 |
| Long-term aged binder (RTFO + PAV) | $G^*(\sin\delta)$ at 25 °C (MPa) | 2.58 |

**Table 6**
Models proposed for volumetric and strength behavior.

| Title | Sum of squares | DF[*] | Mean square | *F* value | Prob > F | Model type |
|---|---|---|---|---|---|---|
| *Volumetric parameters* | | | | | | |
| *Air void* | | | | | | |
| Regression | 7.23 | 3 | 2.41 | 5.80 | 0.0146 | Quadratic |
| Residual error | 4.16 | 10 | 0.42 | | | |
| Lack of fit | 2.01 | 5 | 0.40 | 0.93 | 0.5288 | |
| *R*-squared | 0.94 | | | | | |
| $G_{mb}$[*] | | | | | | |
| Regression | 4.645E−003 | 3 | 1.548E−003 | 5.89 | 0.0139 | Quadratic |
| Residual error | 2.627E−003 | 10 | 2.627E−004 | | | |
| Lack of fit | 1.144E−003 | 5 | 2.287E−004 | 0.77 | 0.6088 | |
| *R*-squared | 0.80 | | | | | |
| *VFA*[**] | | | | | | |
| Regression | 282.73 | 3 | 94.24 | 6.39 | 0.0108 | Quadratic |
| Residual error | 147.46 | 10 | 14.75 | | | |
| Lack of fit | 58.85 | 5 | 11.77 | 0.66 | 0.6678 | |
| *R*-squared | 0.96 | | | | | |
| *Strength parameters* | | | | | | |
| *Stability* | | | | | | |
| Regression | 10.91 | 3 | 3.64 | 4.72 | 0.0152 | Linear |
| Residual error | 12.32 | 16 | 0.77 | | | |
| Lack of fit | 7.62 | 11 | 0.69 | 0.74 | 0.6885 | |
| *R*-squared | 0.77 | | | | | |
| *Flow* | | | | | | |
| Regression | 5.71 | 3 | 1.90 | 7.52 | 0.0023 | Linear |
| Residual error | 4.05 | 16 | 0.25 | | | |
| Lack of fit | 2.77 | 11 | 0.25 | 0.98 | 0.5504 | |
| *R*-squared | 0.89 | | | | | |
| *Marshall quotient* | | | | | | |
| Regression | 5.30 | 3 | 1.77 | 6.96 | 0.0033 | Linear |
| Residual error | 4.07 | 16 | 0.25 | | | |
| Lack of fit | 2.54 | 11 | 0.23 | 0.76 | 0.6759 | |
| *R*-squared | 0.80 | | | | | |

[*] Degree of freedom.
[**] Bulk specific gravity.
[***] Void of aggregate filled with asphalt binder.

**Table 7**
Analysis of variance for air voids, Gmb and VFA.

| Factor | Sum of Squares | DF**** | Mean Square | *F* value | Prob > F |
|---|---|---|---|---|---|
| *Air void* | | | | | |
| A* | 51.98 | 1 | 51.98 | 125.10 | <0.0001 |
| B** | 1.37 | 1 | 1.37 | 3.29 | 0.0996 |
| C*** | 0.17 | 1 | 0.17 | 0.41 | 0.5380 |
| A2 | 2.88 | 1 | 2.88 | 6.92 | 0.0251 |
| B2 | 0.38 | 1 | 0.38 | 0.92 | 0.3602 |
| C2 | 0.045 | 1 | 0.045 | 0.11 | 0.7501 |
| AB | 0.18 | 1 | 0.18 | 0.43 | 0.5253 |
| AC | 0.32 | 1 | 0.32 | 0.77 | 0.4008 |
| BC | 5.000E−003 | 1 | 5.000E−003 | 0.012 | 0.9148 |
| $G_{mb}$ | | | | | |
| A | 4.410E−003 | 1 | 4.410E−003 | 16.79 | 0.0022 |
| B | 8.100E−004 | 1 | 8.100E−004 | 3.08 | 0.1096 |
| C | 9.000E−005 | 1 | 9.000E−005 | 0.34 | 0.5713 |
| A2 | 2.045E−003 | 1 | 2.045E−003 | 7.79 | 0.0191 |
| B2 | 1.455E−004 | 1 | 1.455E−004 | 0.55 | 0.4739 |
| C2 | 2.045E−005 | 1 | 2.045E−005 | 0.078 | 0.7859 |
| AB | 1.250E−005 | 1 | 1.250E−005 | 0.048 | 0.8317 |
| AC | 3.125E−004 | 1 | 3.125E−004 | 1.19 | 0.3010 |
| BC | 1.250E−005 | 1 | 1.250E−005 | 0.048 | 0.8317 |
| *VFA* | | | | | |
| A | 3073.01 | 1 | 3073.01 | 208.40 | <0.0001 |
| B | 43.68 | 1 | 43.68 | 2.96 | 0.1160 |
| C | 3.14 | 1 | 3.14 | 0.21 | 0.6545 |
| A2 | 129.89 | 1 | 129.89 | 8.81 | 0.0141 |
| B2 | 11.81 | 1 | 11.81 | 0.80 | 0.3918 |
| C2 | 4.49 | 1 | 4.49 | 0.30 | 0.5933 |
| AB | 1.13 | 1 | 1.13 | 0.076 | 0.7880 |
| AC | 6.84 | 1 | 6.84 | 0.46 | 0.5111 |
| BC | 0.045 | 1 | 0.045 | 3.052E−003 | 0.9570 |

* Asphalt binder.
** Rediset content.
*** Compaction temperature.
**** Degree of the freedom.

environmental science [13,14], concrete technology [15], material science [16], mechanics [17], biomass [18] and clay science [19]. In asphalt research, Khodai et al. [20] used RSM to evaluate the effects of aggregate gradation and lime content on the tensile strength ratio and indirect tensile strength of dry and saturated hot mix asphalt [20]. Chavez et al. applied the RSM for evaluating the aging responses of asphalt binder [21,22]. Therefore, RSM has been successfully used in various fields of applied sciences, in addition to the availability of scientific supports for RSM in statistical handbooks. This implies that RSM can be potentially applied to evaluate the properties of WMA and proposing a new approach for the determination of the OBC of WMA.

In a typical mix design method, the optimum binder content of a particular asphalt mixture and binder types, is determined from the relationships between mixture volumetric and strength properties with variations in binder contents. The procedure consumes a lot of labor, materials and time. This paper presents an alternative approach for OBC determination by developing a general model of volumetric and strength behavior for a given materials (Rediset content and binder content) and parameter investigated (compaction temperatures) using RSM. In this approach, the required criteria for selecting OBC were first defined and the OBCs were determined for each individual condition as shown in Fig. 1 The use of RSM not only decreases the number of samples required for testing, but also provides the possibility of determining the OBC in each selected condition.

## 2. Response surface method

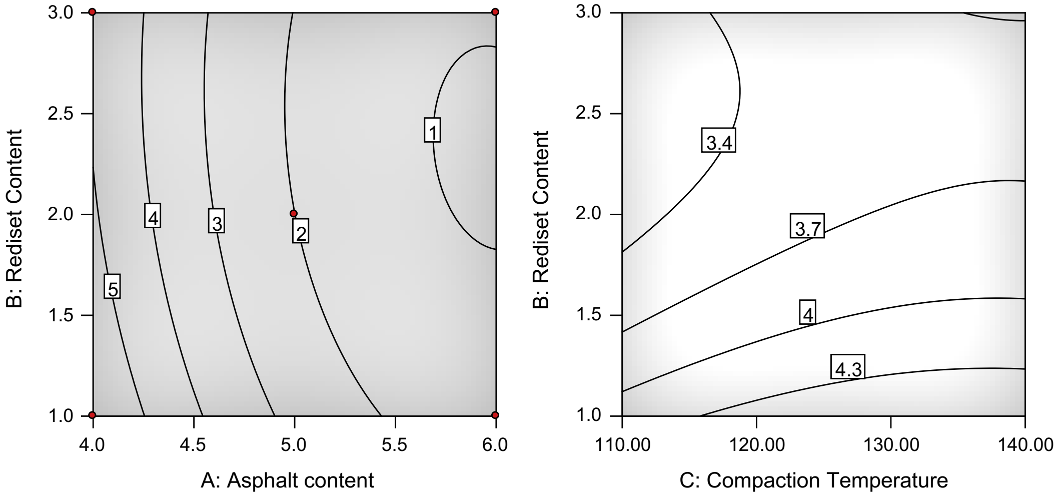
RSM is a set of techniques for developing a series of experimental designs, determining relationship between experimental factors and responses, and using these relationships for finding the optimum conditions [23]. Central composite method (CCD) is usually used to design of experiment in RSM. This method is a fractional factorial experiment design [24] that has the ability to provide a suitable relationship between responses and several experimental factors at different levels [20]. Factorial designs provide useful information on the interaction of factors. Therefore, they are more efficient than one-factor-at-a-time evaluation methods [25]. The arrangement of experiment runs of CCD is available elsewhere [23–25].

The data results from the experimental tests are used to develop mathematical equations via statistical techniques. The fitted equations can be plotted as a curve, contour, or surface by using statistical soft wares. Eqs. (1) and (2) show simple forms of linear and quadratic models for three independent factors, respectively [25]:

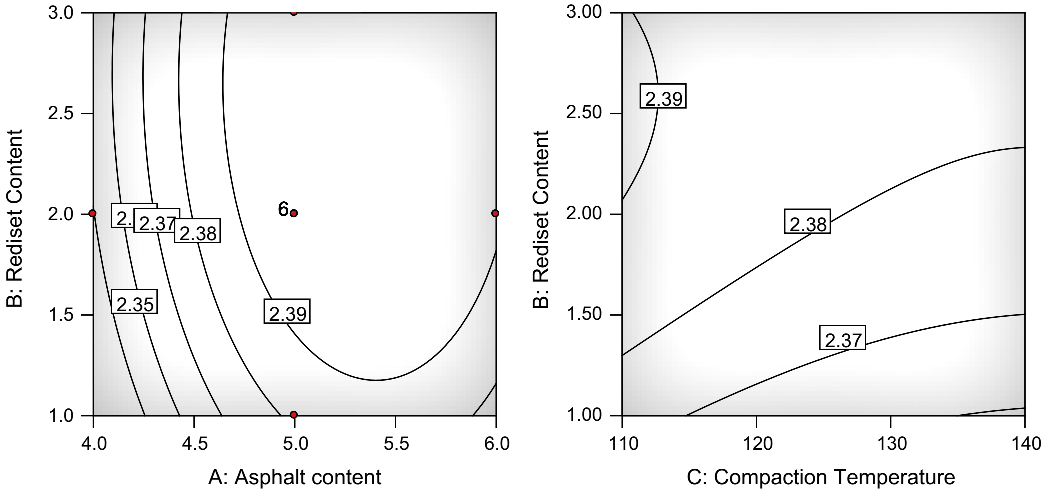
$$Y = C_0 + C_1X_1 + C_2X_2 + C_3X_3 \tag{1}$$

$$Y = C_0 + [C_1X_1 + C_2X_2 + C_3X_3] + [C_{12}X_1X_2 + C_{13}X_1X_3 + C_{23}X_2X_3] + [C_{11}X_1^2 + C_{22}X_2^2 + C_{33}X_3^2] \tag{2}$$

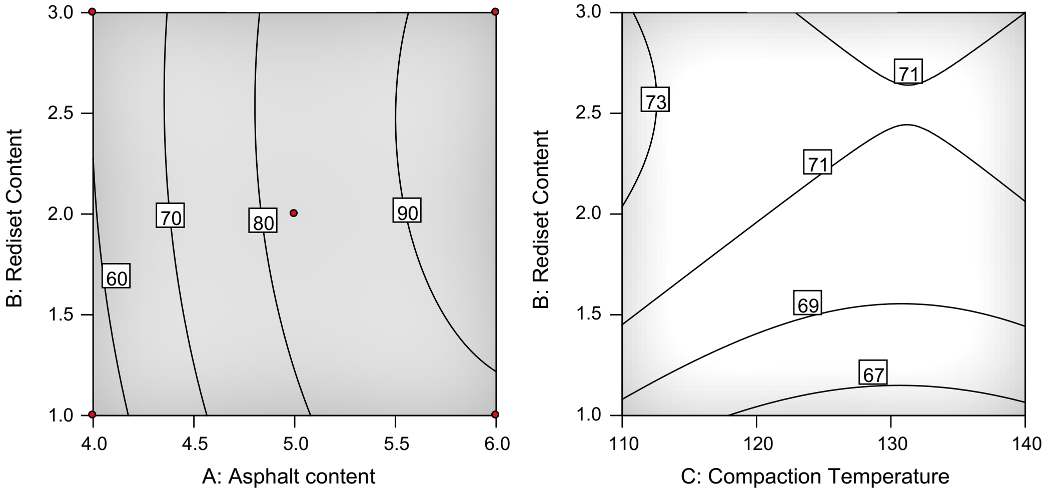
where $Y$ is the response; $X_1$, $X_2$, and $X_3$ are the independent factors; and $C_0$, $C_i$, $C_{ii}$, and $C_{ij}$ are the intercept, linear, quadratic, interaction coefficients respectively. In this study, appropriate models were selected by the sequential *F*-tests, lack of fit tests, and the value of *R*-squared. Analysis of variance (ANOVA) was performed on the experiment data. Predictive responses were then used to determine the OBCs of the target conditions.



(a) Air voids at compaction temperature = 110 °C (b) Air voids at binder content= 4.5%



(c) $G_{mb}$ at compaction temperature = 110°C (d) $G_{mb}$ at binder content = 4.5%



(e) VFA at compaction temperature = 110 °C (f) VFA at binder content = 4.5%

**Fig. 2.** Volumetric properties patterns of WMA incorporating Rediset.

**Table 8**
Analysis of variance for strength behavior.

| Factor | Sum of squares | DF | Mean square | *F* value | Prob > F |
|---|---|---|---|---|---|
| *Stability* | | | | | |
| A[*] | 4.638 | 1 | 4.638 | 18.250 | 0.0006 |
| B[**] | 0.132 | 1 | 0.132 | 0.520 | 0.4811 |
| C[***] | 0.534 | 1 | 0.534 | 2.100 | 0.1666 |
| *Flow* | | | | | |
| A | 5.069 | 1 | 5.069 | 20.013 | 0.0004 |
| B | 0.475 | 1 | 0.475 | 1.876 | 0.1897 |
| C | 0.169 | 1 | 0.169 | 0.667 | 0.4260 |
| *Marshall quotient* | | | | | |
| A | 5.595 | 1 | 5.595 | 7.267 | 0.0159 |
| B | 0.085 | 1 | 0.085 | 0.110 | 0.7445 |
| C | 5.227 | 1 | 5.227 | 6.790 | 0.0191 |

[*] Asphalt binder.
[**] Rediset content.
[***] Compaction temperature.
[****] Degree of the freedom.

### 3. Materials used and experimental procedures

The central composite method with six replicate samples for center point was used to design the experiment. Table 1 illustrates the matrix of experiment for warm mix asphalt study taking into consideration three factors namely; Rediset content (1–3%), compaction temperature (110 °C to 140 °C) and asphalt binder content (4–6%). The center or mid-point refers to the median of all factors considered.

The Marshall test results and volumetric measurements were selected as the responses (dependent variable). These variables were defined based on the Malaysian road works specifications for the design of dense mixture [26]. Table 2 lists these variables and their acceptable ranges. The values presented in Table 2 are considered as the basic criteria for determining the OBC.

Granite aggregate supplied by Kuad Sdn. Bhd. was used in the mix design for AC 14 mix based on local standard specifications [26]. Tables 3 and 4 show the aggregate gradation and engineering properties of the aggregate used. Table 5 shows the properties of the AC80/100 asphalt binder used. Rediset which is a product of the Akzo Nobel from the Netherlands was used as the chemical warm mix additive. Due to the fact that Rediset is a combination of surfactants and organic additives, it can improve the wettability of the aggregate surfaces by the binder through active adhesion, and through decreasing the binder viscosity [27].

The procedures applied to prepare the samples based on the parameters mentioned in Table 1 took the following steps:

- Blending the predefined Rediset content with the asphalt binder at 130 °C for 30 min using a propeller mixture.
- Preparing the mixtures for each set of mixing temperatures (10 °C higher than the compaction temperature), Rediset and binder contents.
- Short-term aging the loose mixtures for 2 h at the anticipated compacted temperature.
- Compacting the mixtures at the compaction temperature using the Superpave gyratory compactor at 30 revolutions per minute and compaction angle of 1.5° for 100 gyrations.

In addition, conventional HMA samples were compacted at 150 °C and their responses were recorded as well.

RSM was applied for statistical analysis of the responses. These analyses were carried out by the Design-Expert 6.0.6software. For each of the responses, the significance of the model and factors were examined, and the required graphs were developed. The next step was to determine the OBC using the predicted response from each model.

## 4. Results and discussion

### 4.1. Analysis of volumetric properties

Based on the specifications; air voids, bulk specific gravity ($G_{mb}$) and void of aggregate filled with asphalt binder (VFA) are volumetric properties that are used for determining the OBC [26]. These parameters have been used in some other mix design methods as well. The volumetric properties of all samples were analyzed through the RSM. As illustrated in Table 6, the proposed models for the volumetric behaviors are quadratic.

The analysis of variance (ANOVA) results for all volumetric parameters are presented in Table 7. ANOVA results indicated that binder content has significant effects on the volumetric responses. The influences of these factors (Rediset content, compaction temperature and asphalt binder content) on the air voids, $G_{mb}$ and VFA are shown in Fig. 2.

Fig. 2a shows the contour plot of Rediset and binder content versus air voids of samples compacted at 110 °C. From this graph, the air void increases with decreasing Rediset content from 2% to 1% and decreasing binder content from 6% to 4%. For instance, at 4.5% asphalt content, the air voids increases by approximately 3.3–4.1% as the Rediset content decreases from 2.0% to 1.0%. Also, at 1.5% Rediset content, the air voids increases by approximately 1.5% to 5.3% as the asphalt content decreases from 6.0% to 4.0%. This implies that at a particular compaction temperature, it is possible to achieve the target air voids by changing the Rediset and binder contents. At higher compaction temperatures, similar trends are observed.

Fig. 2b presents the interaction effects of Rediset content and compaction temperature at 4.5% binder content. This binder content is approximates to the OBC that will be discussed in Section 4.3. From Fig. 2b, at a given binder content, higher air voids is related to higher compaction temperature and lower Rediset content.

Fig. 2d illustrates the variation of bulk specific gravity with compaction temperature and Rediset content. From Fig. 2d, warm mix asphalt produced at lower compaction temperatures with higher Rediset contents exhibit slightly higher $G_{mb}$ compared to mixtures compacted at high temperature with lower Rediset content. Additionally in Fig. 2c and d, the maximum $G_{mb}$ (at compaction temperature110 °C) occurs at 2.51% Rediset content and 5.26% binder content.

Fig. 2e and f are developed to demonstrate the effects of research parameters on the VFA. In these figures, mixtures containing lower Rediset content (at 4.5% binder content) exhibit lower VFA, while the influence of Rediset content on the VFA at a particular compaction temperature is negligible. As expected, an increase in the binder content results in an increase in VFA.

### 4.2. Analysis of strength behavior

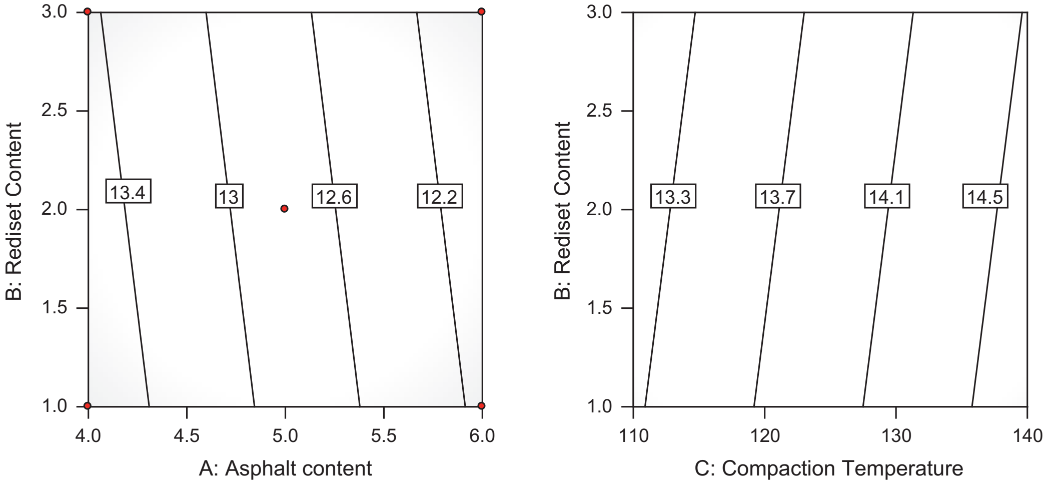
The stability and flow response of each sample was measured using the Marshall stability machine. The Marshall quotient was calculated using the following equation.

$$\text{Marshall Quotient} = \text{Stability}/\text{Flow} \quad (3)$$

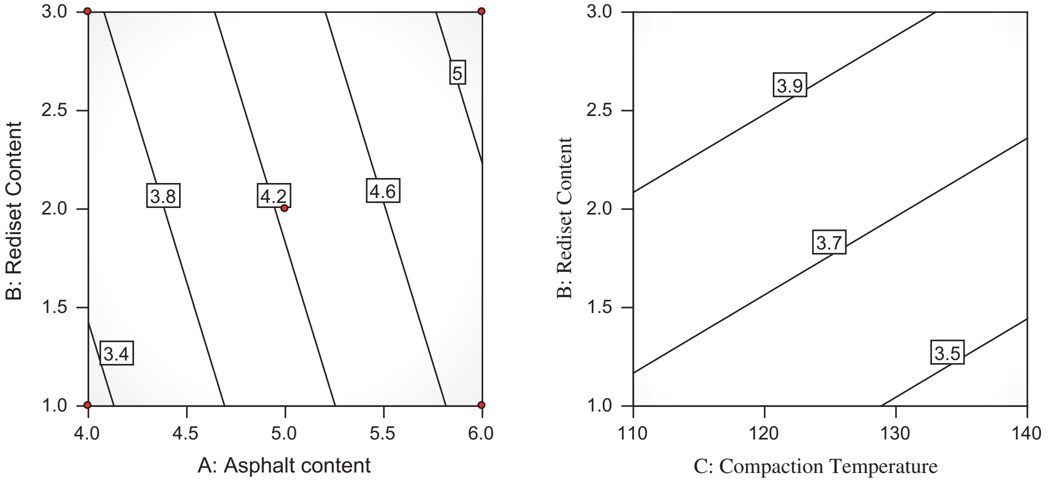
A statistical analysis based on RSM was conducted on the laboratory test results and linear models are developed for evaluating mixture strength behavior. The results of the analysis are shown in Table 6. In the next step, an ANOVA was performed on the results and the output is shown in Table 8. The ANOVA results showed that compaction temperature and binder content have significant effects on the Marshall quotient.

Fig. 3 shows the interactive effects of Rediset content, binder content and compaction temperature on mixture strength. The 110 °C temperature selected is the lower compaction temperature to optimize the lower energy consumption and emission production. Also, 4.5% binder content was used to plot the graph as the binder content which is close to the OBCs. In Fig. 3a, c, and e at 110 °C; by decreasing the Rediset and binder contents, the Marshall stability and quotient increase, while the flow decreases. This trend is observed at higher compaction temperatures. In Fig. 3b, d, and f, at a given binder content by increasing the Rediset content and decreasing the compaction temperature, the stability and Marshall quotient decreases while the flow increases. Other binder contents exhibit similar trends.

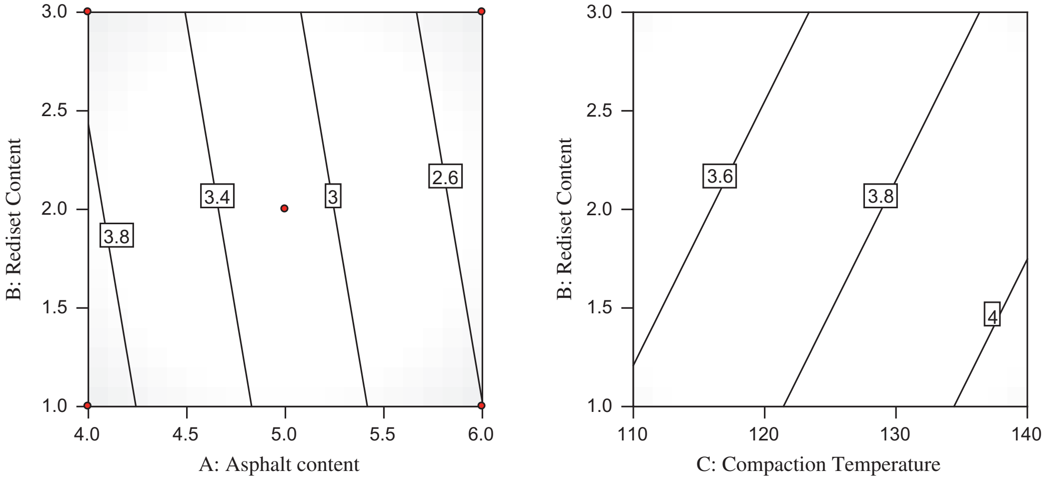
Fig. 4 shows the relationship between $G^*/\sin\delta$ and Rediset content for samples subjected to short-term aging at 60 °C, where $G^*$ is measured by the DSR machine. As can be seen, asphalt binder



(a) Stability at compaction temperature = 110 °C (b) Stability at binder content = 4.5%



(c) Flow at compaction temperature = 110 °C (d) Flow at binder content = 4.5%



(e) Marshall Quotientat compaction temperature= 110°C (f) Marshall Quotientat binder content= 4.5%

**Fig. 3.** Strength behavior of WMA incorporating Rediset.

blended with higher Rediset content exhibit lower $G^*/\sin\delta$. $G^*/\sin\delta$ is a reflection of binder stiffness at high temperatures. It may therefore, be possible to determine the correlation between $G^*/\sin\delta$ of short-term aged binders and stability and Marshall quotient at 60 °C. The conventional binder and binder blended with Rediset were artificially aged in the laboratory using the Rolling Thin Film Test (RTFO) according to ASTM D2872 (2006) procedures.

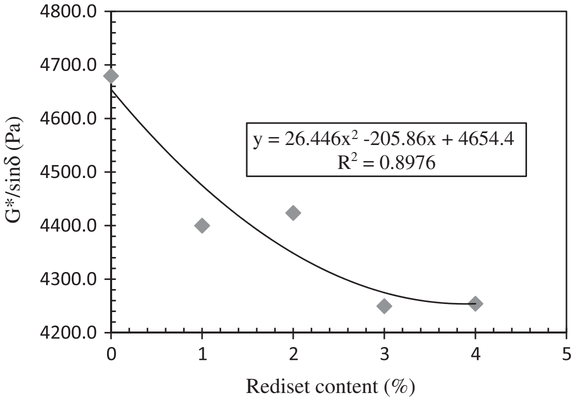


**Fig. 4.** Relationship between G*/sin δ and Rediset content (short-term aging, test temperature 60 °C).

**Table 9**
OBC for defined conditions.

| Defined condition | | Optimum binder content (%) |
|---|---|---|
| Compaction temperature (°C) | Rediset content (%) | |
| 110 | 1 | 4.55 |
| 110 | 2 | 4.4 |
| 110 | 3 | 4.4 |
| 125 | 1 | 4.65 |
| 125 | 2 | 4.5 |
| 125 | 3 | 4.5 |
| 140 | 1 | 4.65 |
| 140 | 2 | 4.5 |
| 140 | 3 | 4.5 |

### *4.3. Determination of optimum binder content*

The optimum binder content for each compaction temperature and Rediset content are calculated based on the strength and volumetric properties of WMA to satisfy local specifications for dense mixtures [26]. The OBC is identified by taking the following steps:

- Modeling the air voids, $G_{mb}$, VFA, stability, flow, and Marshall quotient as a function of binder content, compaction temperature and Rediset content using the RSM.
- Identifying the target compaction temperature and Rediset content to determine the OBC.
- Plotting contour plots for each strength and volumetric response at target compaction temperatures.
- Using contour plots for determining the corresponding binder content for each target Rediset content at maximum stability, maximum $G_{mb}$, flow equivalent to 3 mm, VFA equivalent to 75%, and air voids equivalent to 4% followed by obtaining the average as the initial OBC.
- Controlling the strength and volumetric responses of initial OBC with a criterion mentioned in Table 5 to confirm or finalize the OBC.

According to this procedure, the finalized OBCs for each compaction temperature and Rediset content are listed in Table 9. The results showed that variations in OBC for different compaction temperature and Rediset content are limited to between 4.5% and 4.65%. Furthermore, at a fixed compaction temperature, a higher optimum binder content is related to lower Rediset content while a high compaction temperature requires lightly higher OBC. When the conventional Marshall mixture design method is used to determine the OBC, the number of fabricated samples required for nine different sets of materials and methods equals 9 × 15 or 135 samples. With RSM, only 20 Marshall samples are required to be fabricated.

The optimum binder content of HMA without Rediset compacted at150 °C was obtained by fabricating 15 samples at binder contents ranging from 4% to 6% and by evaluating their strength and volumetric responses. From analysis of the results, the OBC equals 4.7%, and which is slightly higher than the OBC of mixture incorporating Rediset.

In the next step, a total of 15 warm mix asphalt samples were fabricated at 110 °C with 2% Rediset content at different binder contents and the OBC was individually calculated for this case. The results showed that the OBC difference between this value (4.5%) and the OBC calculated via RSM (4.4%) for the same compaction temperature and Rediset content is 0.1%.

## 5. Conclusions and recommendations

A new approach was developed for determining the optimum binder content using RSM. This method has the ability to quickly determine the OBC for different set of materials and methods. Simultaneously, the strength and volumetric properties of mixtures can be statistically analyzed. The following conclusions can be drawn:

- Although the warm mix asphalt at lower compaction temperature needs lower optimum binder content to conform to the mix design criteria, its stability and quotient is lower than mixtures fabricated at higher temperatures. As we know, lower compaction temperature leads to less energy consumption and lower emissions production at the asphalt mixing plants. Also for this case, the OBC of WMA is slightly lower than the OBC for HMA without warm additive Rediset.
- Using higher Rediset content slightly decreases the asphalt mixture Marshall stability, Marshall quotient and air voids but increases their VFA. It implies that higher Rediset content has a softening role in the asphalt mixtures. Therefore, it is essential to characterize the resistance to permanent deformation of warm mix asphalt modified with Rediset.
- For a detailed validation of this approach, the authors recommend investigating the effects of other factors like binder types, aggregate gradation, additive types as well as other mix design criteria by using RSM.

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